EESTI MAAÜLIKOOL
Tehnikainstituut

David Puusaag

DETERMINING THE ABSORPTION WAVELENGTH IN SOLAR CELL NANOMATERIALS – METAL NANOPARTICLES

NEELDUSKIIRGUSE MÄÄRAMINE NANOMATERJALIDES – METALLNANOOSAKESED

Bachelor's thesis
Engineering / tech and technology curriculum, energy application management

Supervisors: Protima Rauwel, *PhD*
Erwan Yann Rauwel *PhD*
Harleen Kaur *MSc*

Tartu 2021

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Kreutzwaldi 1, Tartu 51006</td><td colspan="2">Bakalaureuse töö lühikokkuvõte</td></tr>
<tr><td colspan="2">Autor: David Puusaag</td><td colspan="2">Õppekava: Tehnika ja tehnoloogia, energiakasutus</td></tr>
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Juhendajad: Protima Rauwel, PhD, Erwan Yann Rauwel, PhD, Harleen Kaur, MSc
Kaitsmiskoht ja -aasta: Tartu 2021</td></tr>
<tr><td colspan="4">Päikesepaneelide tehnoloogia on lai uurimisvaldkond. Plasmoonika on kindel liituja selles valdkonnas. AgNP-del või hõbemetallnanoosakestel on osatähtsus selles valdkonnas. Selles töös uuritakse AgNP-sid, nendega seotud nähtusi sh plasmon- või valgusresonants, ja nende rolli päikesetehnoloogias. Samuti on mõõdetud ning analüüsitud kolme AgNP proovi valguskiirguse neeldustugevust. On võrreldud teoreetiliste pooltega ning eripäradega. On analüüsitud osakeste morfoloogia ning muu osakaalu resonantstipu muutmisel.</td></tr>
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Estonian University of Life Sciences
Kreutzwaldi 1, Tartu 51006

Abstract of Bachelor's thesis

Author: David Puusaag

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Place and date: Tartu 2021

Solar cell technology is an ever-increasing field. Plasmonics is an upcoming heavy-hitter in this area. AgNPs play a role in plasmonics. It is in this thesis that AgNPs and their role in solar cells are looked into. Notions such as LSPR and pertaining phenomena are looked at. AgNPs samples have been provided of which UV-Vis Spectroscopy was performed, and samples measured. Theoretical details and the validity of information and details are analyzed. Absorption spectra analyzed with minute particle morphology analysis.

Keywords: AgNP, LSPR, absorption spectra, resonance, wavelength, particle morphology

TABLE OF CONTENTS

ABBREVIATIONS AND TERMS

AgNP – argentum (silver) nanoparticle

LSPR – localized surface plasmon resonance

SPP – surface plasmon polariton

DSSC – dye sensitized solar cell

PCE – power conversion efficiency

EM – electromagnetic

PV – photovoltaic

E-field – electric field

INTRODUCTION

Solar cells have a huge impact on society and the environment, with worldwide photovoltaic device (PV) production increasing exponentially every year. Scientists and entrepreneurs are rushing to create PV that is increasingly viable, efficient and cost-effective. Plasmonics has been quite an interesting field during the past few decades, promising great changes in many areas. It is the conjunction of plasmonics and solar cells that could bring enhancement to technologies involved. In this work, AgNPs and the LSPR mechanisms are looked into. The literature is reviewed and the results of three samples are analyzed, out of which two are synthesized from Thuja and Artemisia plant extracts and one is chemically synthesized. UV-Vis Spectroscopy provides the absorption spectra graphs produced from these AgNPs. The thesis will be concluded with analytical discussion.

More, specifically, the aim of this thesis is to study the absorption range of AgNPs of three different samples via UV-Vis spectroscopy and discuss the R&D state of the art of solar cell technology. Along the thesis, an overview of current solar cell technologies is given, the importance, properties and applications of AgNPs are discussed, literature is reviewed and finally work results and the related details are analyzed.

1. SOLAR CELL TECHNOLOGY

1.1. Working principle

The basic working principle of a solar cell for conventional cells is that they have a positive layer and a negative layer of charges. These layers act in a way such that a p-n junction is formed, essentially forming an electric field. When light hits the cell and is absorbed, electrons get ejected and flow through the p-n junction. The flow of charges produces a photocurrent in a forward biased configuration.

1.2. Overview of current solar cell technologies

The information displayed here reflects information on the National Renewable Energy Laboratory website [16] and is their representation of the current existing technologies in the world, which they have categorized, to which extra information has been added.

- a-Si: Amorphous Silicon

Cells grown on low cost substrates such as glass, metal and plastic. Thin film, flexible, lightweight. Low efficiency and low deposition rate.

- Chalcogenide

These are cells that incorporate an element from the 6^{th} column of the periodic table. Examples are cells such as CIGS (Copper Indium Gallium Selenide) or CdTe. Thin film, on glass or plastic, direct bandgap semiconductors, mainstream PV technology. CdTe cells have recently become better than polycrystalline silicon cells in terms of cost-effectiveness. [15]

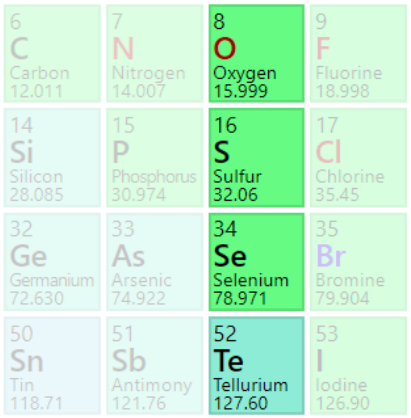

Figure 1.1. 6th column of the periodic table. [1.1]

- Dye-sensitized solar cell

Graetzel/DSSC cells use porous semiconductor materials such as ZnO, SnO_2 and TiO_2. Thin film, with an absorbing dye coat and a charge separating electrolyte. Their major advantages are low cost, ease of production, low toxicity. [17]

- III-V

Wide range bandgap cells through the use of multi-junctions include the 3rd and 5th column of the periodic table. An example is GaAs that is grown on germanium and is a direct band gap semiconductor. However, it is costly even though highly efficient. It has the ability to operate at high temperatures. It possesses a record single junction performance and best environmental performance adapted to space missions.

Figure 1.2. 3rd and 5th columns of the periodic table. [1.2]

- Hybrid

Combination of III-V and silicon cells, which may include perovskite structures in the future (perovskite cells).

- OPV cells (organic photovoltaic cell)

Polymeric and/or organic materials are commonly a bulk heterojunction cell using polymer, fullerene. They are lightweight, flexible and with high potential.

- Perovskite

Cells with perovskite lattice structure. Has high potential and is being rigorously researched. 20% efficiencies have already been achieved with lower costs than Si cells. [18] Cell structure is usually denoted as ABX_3: A an organic/inorganic cation, B metal cation, X halide. There are different compounds and combinations.

- Crystalline Silicon

Comprises 90% of today's PV market. Two types of cells are distinguished: polycrystalline and monocrystalline, with the former having defects in the lattice structure, making it cheap but less efficient. Si has an indirect bandgap, which is the reason for the cell's thickness.

2. SILVER NANOPARTICLES

2.1. Prelude

Nanoparticles have been very important in the last few decades. There have been a multitude of associated novelties and discoveries: C_{60} buckminsterfullerene in the use of solar cell technology [1], graphene tubes (carbon nanotubes), plasmonics [2], that have had a a quite significant impact on science and technology. Plasmonics have been duly researched as it is a field that should bring a huge benefit to a lot of interdisciplinary fields, including optoelectronics. The benefit lies in the ability of plasmonics to harness, control and utilize light to the fullest extent – light interaction in the nanoscale. Silver is able to exhibit plasmonic resonance in a very wide range of wavelength, thus making AgNPs suitable for several applications.

2.2. Importance

Silver is able to exhibit localized surface plasmon resonance (LSPR) in a very wide range of wavelength. [3] Conventional single-junction Si cells absorb poorly in the 600-1100 nm range, due to having an indirect bandgap, which is the reason for their thickness (180-300 μm) [4], but direct bandgap materials do not have that issue as their electrons do not need extra energy or momentum for the transition. That is the reason for direct bandgap cells being thin film, ie. they require less energy for a valence band to conduction band transition. The reason for the indirect bandgap in the silicon lattice is because the top of the valence and the bottom of the conduction band do not have the same k vector: they are slightly shifted, thus requiring a lattice vibrational

shift. AgNPs, regardless of technology used, could yield a great energy enhancement in the overall structure.

The presence of AgNPs would allow to tap into the unabsorbed or poorly absorbed regions of light, where the key lies in making use of LSPR. The key aspect of LSPR lies in its ability to harness light and then scatter it or make localized antennae where the near-field (E-field) of neighboring atoms are also affected, acting as hotspots and giving a wide range absorption enhancement.

Other than silver being a noble metal, what is common to most metals is that their valence electrons are loosely tied to their nucleus, enabling great thermal and electrical conduction (as we move further away into the periodic table, materials get heavier with new orbitals being introduced and the electrons' bond to the nucleus weakening). Such electrons are able to oscillate freely, giving rise to plasmon resonance – *localized surface plasmon resonance* – where plasmon meaning an oscillating electron cloud that absorbs and scatters incident light while resonance being the resonance to a certain frequency of light, and surface referring to the interface of a dielectric and a metal. Scattering occurs because oscillating electrons generate EM waves.

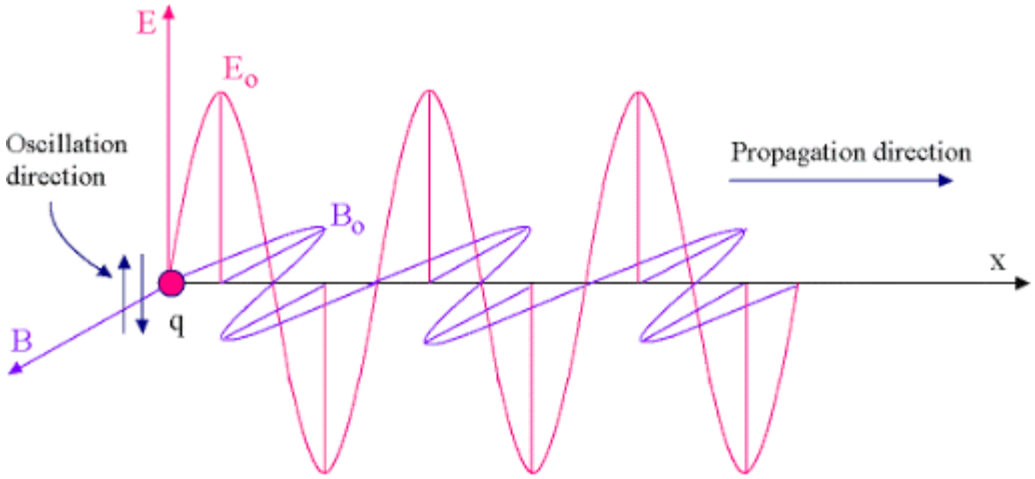

Figure 2.1. An oscillating charge q that is a source of radiation. [2.1]

In LSPR, oscillation of the electrons synchronizes with the oscillation of the incident light. At the resonance point, the displacement of the electrons relative to the nuclei is at the highest,

hence the restoring forces are equal in strength. Resonance is determined by the density of electrons, the effective electron mass, the shape and size of the charge distribution. [5]

The ability of silver to harness light exceeds other metals. [6] Using its particles to maximum extent will allow us to augment the scale of conventional technologies, yielding great cost reduction, and generally enhance the performance of non-conventional cells. This is in development. [7][8][9] In Figure 2.2. the LSPR quality factor that correlates with absorption efficiency in metals is depicted. Silver outperforms others, which indicates its potential with different solar cell applications.

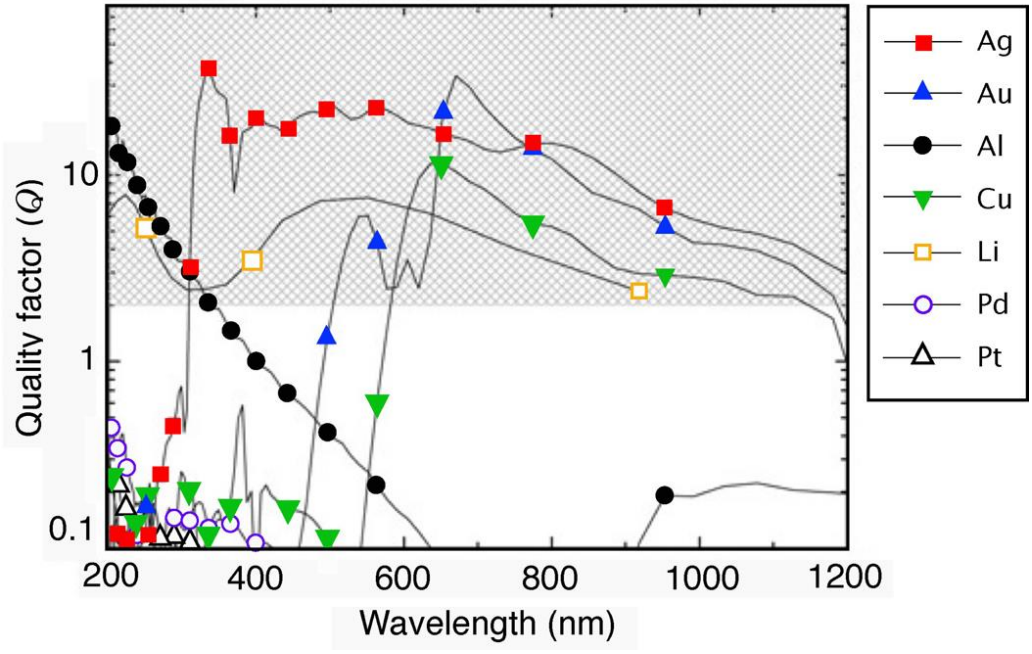

Figure 2.2. LSPR quality factor (~absorption spectra of metals). (© 2009 Elsevier [25]) [2.2]

AgNPs play an important role in increasing the power conversion efficiency of cells. Thus it is imperative to find the best cost-effective solution to manufacture them on a large scale. Green synthesis could contribute. [10]

2.3. Properties

It is important to note that the efficiency range is due to our technology being able to manipulate the dimensions of the particle. Varying the shape and size changes the LSPR peak. [11][20] The dielectric environment contributes where a change could redshift the absorption spectra all the way to 1500 nm. [12] Counter-opposing forces bring forth compensating changes in the particle – interacting electric fields. [13] The larger the surface area of the interaction, the more light is absorbed. Figure 2.3 depicts the working mechanism of LSPR, whereby the electrons of a nanoparticle are being irradiated with incident light inducing a dipole moment (A) and (B) where a perpendicular wave induces the propagation of a surface plasmon polariton along the surface of a metal nanostructure.

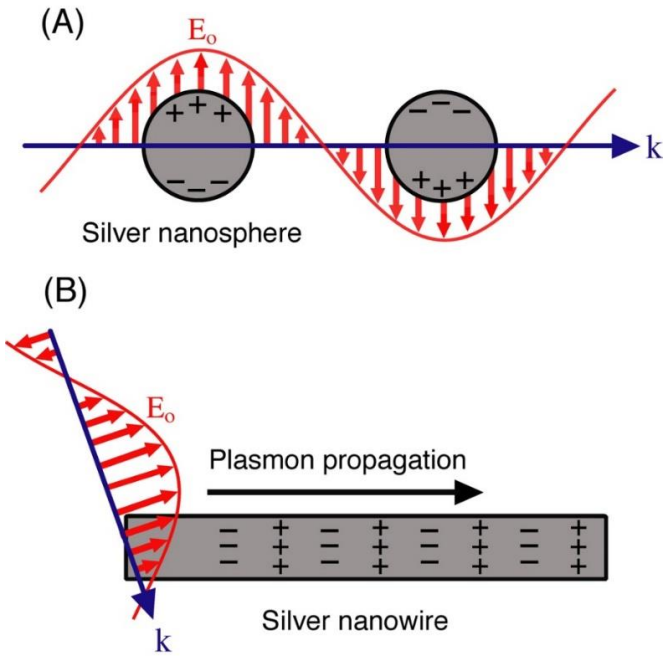

Figure 2.3. The workings of LSPR and SPP. (© 2009 Elsevier [26]) [2.3]

The scattering cross section of a silver nanoparticle can be ten times that of its geometric area. [27] Thus, it would be enough to proportionally scatter a surface with AgNPs 10% of its area, as the near-field enhancement would increase the effective absorption area. [14] Smaller particles scatter light in a backwards-forwards direction while bigger ones radiate outwards as well, as can be seen in the following image:

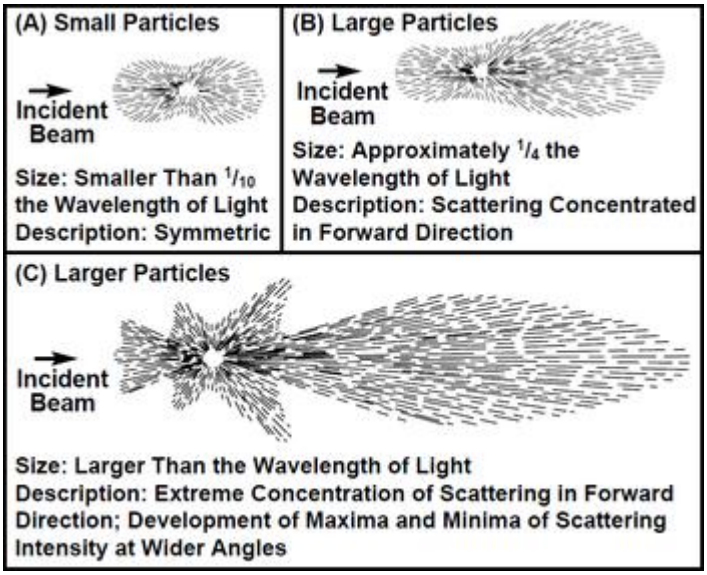

Figure 2.4 Scattering of particles. (A) Rayleigh Scattering, (B) Mie Scattering, (C) Mie scattering. [2.4] (Brumberger, et al. 1968)

(A) and (B) are more relevant, as the size of particle (C) is already exceeding the wavelength of light. Particles smaller than 1/10 the wavelength of light exhibit symmetrical backward-forward scattering, while bigger, ¼ the wavelength of light particles exhibit asymmetrical scattering.

Moreover, ohmic resistance scales with volume *v*, but scattering scales in the square. [21] So large particles are better if light scattering is the prime objective. Nanoparticles can be used as mid-junction antennae that increase the local-field of neighbouring atoms, increasing electron-hole pair generation [22] or on the surface where scattering into the absorber layer is more important.

2.4. Applications

Since the LSPR of AgNPs is dependent on the refractive index and the dielectric of the surrounding medium it can be used in such applications where the change in LSPR wavelength would indicate the presence of a type of object, ie. biosensory applications. It is used in SERS (Surface Enhanced Raman Spectroscopy), whereby the particles of a medium are being

irradiated by light and the LSPR is used in sensing nearby molecules. The use of AgNPs is quite extensive in biomedicine, where the antimicrobial qualities and the oxidation states of silver nanomaterials are found to be useful. Furthermore, AgNPs have been used in bio-imaging applications. Additionally, the range of applications in plasmonics is quite extensive, ranging from imaging, sensing, optics, photonics to optoelectronics. With all the technologies in existence, AgNPs are integral to the research and science. As we head further, there are technologies such as invisibility, quantum photonics, antimicrobial qualities and efficient AgNP enhanced solar cells. Areas are being researched that could benefit cells with the highest potential. In the appendices, two graphs of cell efficiencies have been added for reference – charts showing available module-based technologies and laboratory-based cells.

3. REVIEW OF LITERATURE

3.1. Synopsis

The articles that were reviewed and analyzed are: (1) *Plasmonics for photovoltaic devices* (A. Polman, 2010), (2) *Enhanced Visible Light Absorption and Reduced Charge Recombination in AgNP Plasmonic Photoelectrochemical Cell* (Buda, Shafie et al., 2017) and (3) *Light absorption enhancement in organic solar cells with silver nanoparticles and silver meso-flower* (Tran, Kim, Park, 2017). (1) is a good starting article to wrap ones head around plasmonics and the field of solar cells in general. (2) offers good evidence for a PCE increase, while (3) provides information relating to particle morphology.

4. UV-VIS SPECTROSCOPY

The spectrophotometer Nanocolor UV/Vis II 190−1100 nm below was used to measure the absorbance spectra of the samples.

Figure 4.1. The MN NANOCOLOR UV/VIS II. [4.1]

The light sources are a tungsten for UV and halogen for visible light. On the right we have the cuvette holder, while in the middle the display with its various functions.

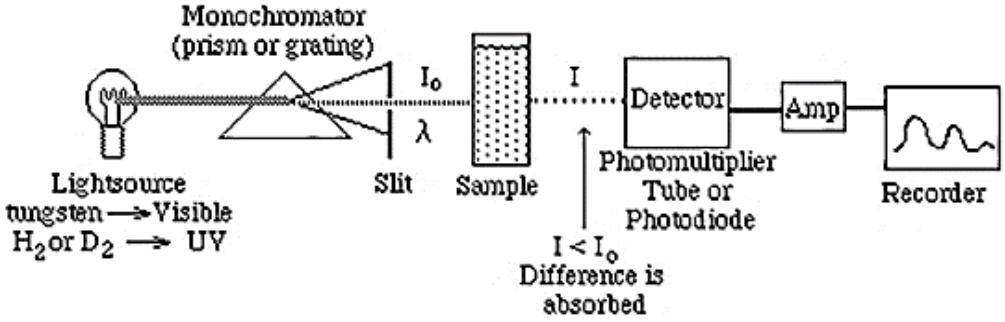

Figure 4.2. Principle of operation. [4.2]

Absorbance is determined by Beer-Lambert law:

$$A = \varepsilon cL$$

where A is absorbance, ε molar attenuation coefficient, c concentration and L path length, with ε depending on the sample and c and L interchangeable.

5. METHODOLOGY

In working with the sample, a simple approach was taken. Each sample was carefully weighed before preparing a solution. We used lab-grade scale to weigh the quantities, with the amounts varying from 5-15 mg. Two of the samples needed to be grinded with a mortar and pestle before dispersion in the solvent. Sonification was used to ensure a colloidal dispersion. At times, that did not work out very well as the interatomic-molecular bonds were strong, and the particles stayed in shape. We tried a different solvent which was either water, isopropyl alcohol or ethanol. Finally, upon achieving or reaching a colloidal solution, we performed measurements, and the results are follows:

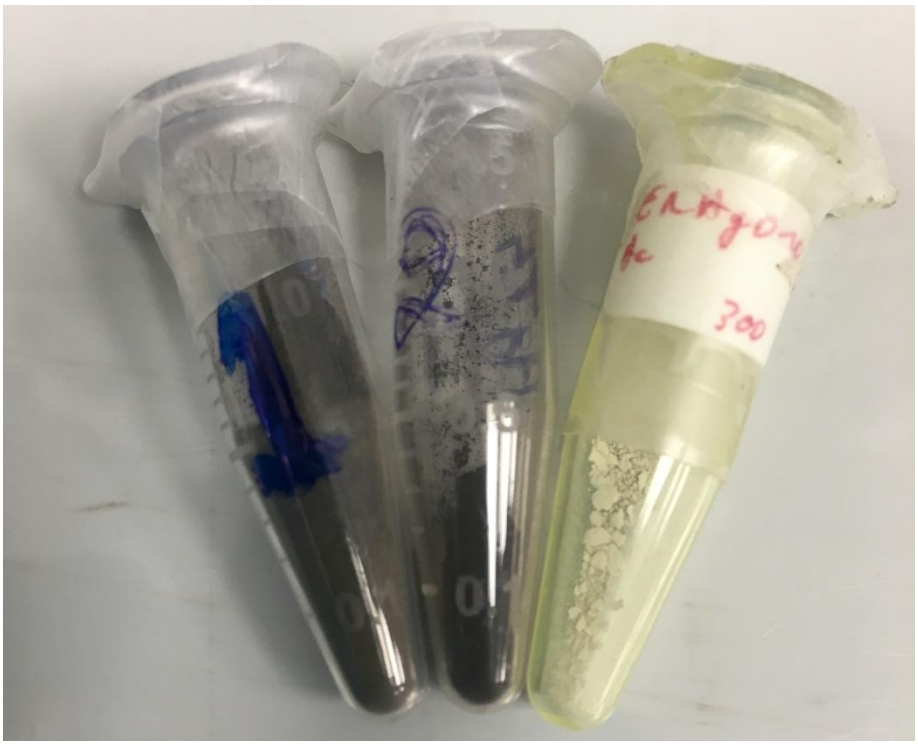

Figure 4.3. The three samples in Eppendorf tubes: AgNPs from an Artemisia extract, Thuja extract and a sol-gel method, respectively.

6. ANALYSIS OF RESULTS

6.1. Artemisia extract

On the right we have the AgNP peak of 455 nm and the peak of the organic material on the left. As can be seen, the absorption spectra for the AgNPs is wide, indicating a non-uniform size distribution or larger, more rugged surface particles. In paper review (3) mesoflowers have a wide absorption range, indicating that these particles too could be bigger and similar in shape. Here the solvent used was water.

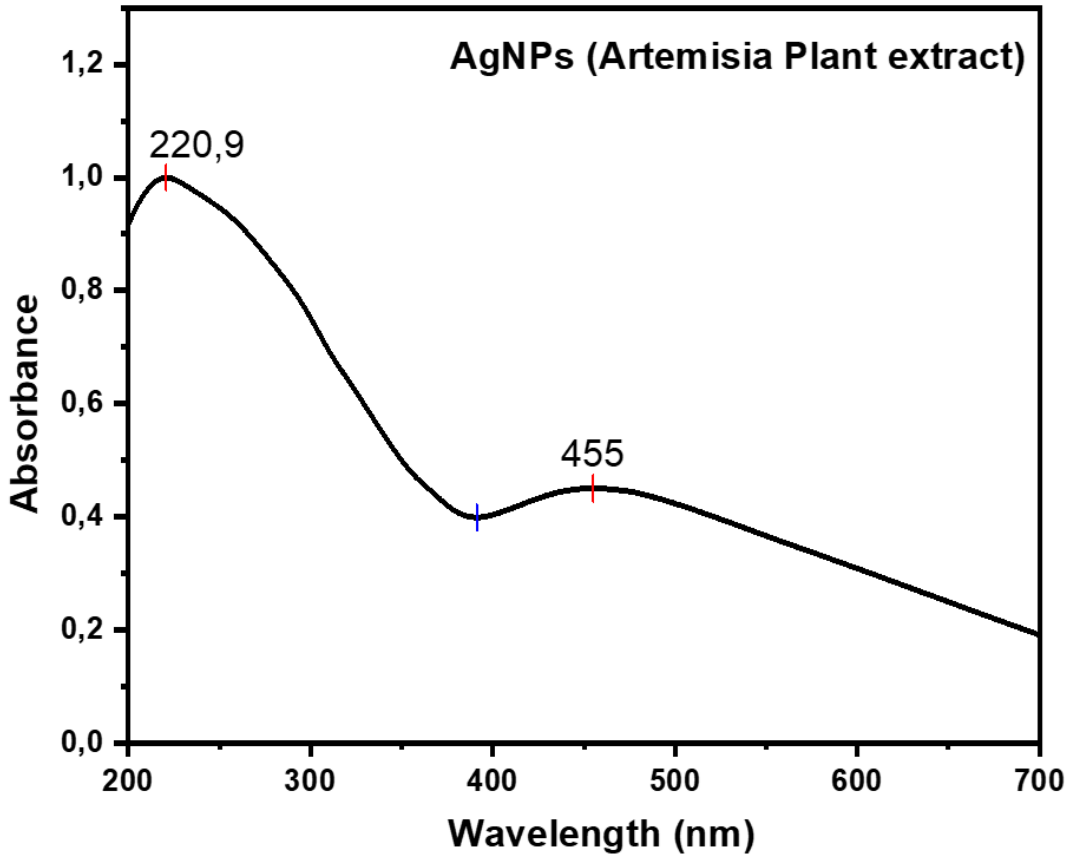

Figure 6.1. AgNP spectra graph of the artemisia sample at 455 nm.

6.2. Thuja extract

On the right we have the AgNP peak of 479.5 nm, while on the left the peak of the organic material. Similarly to the last graph, these are larger, more rugged surface particles, with a different shape. The redshift could be due to the organic material in the solution, owing to a change in the dielectric medium. As the peak is more distinct the size distribution or shape could have been a bit more uniform. Using different solvents such as ethanol or isopropyl alcohol showed no difference in the absorption spectra.

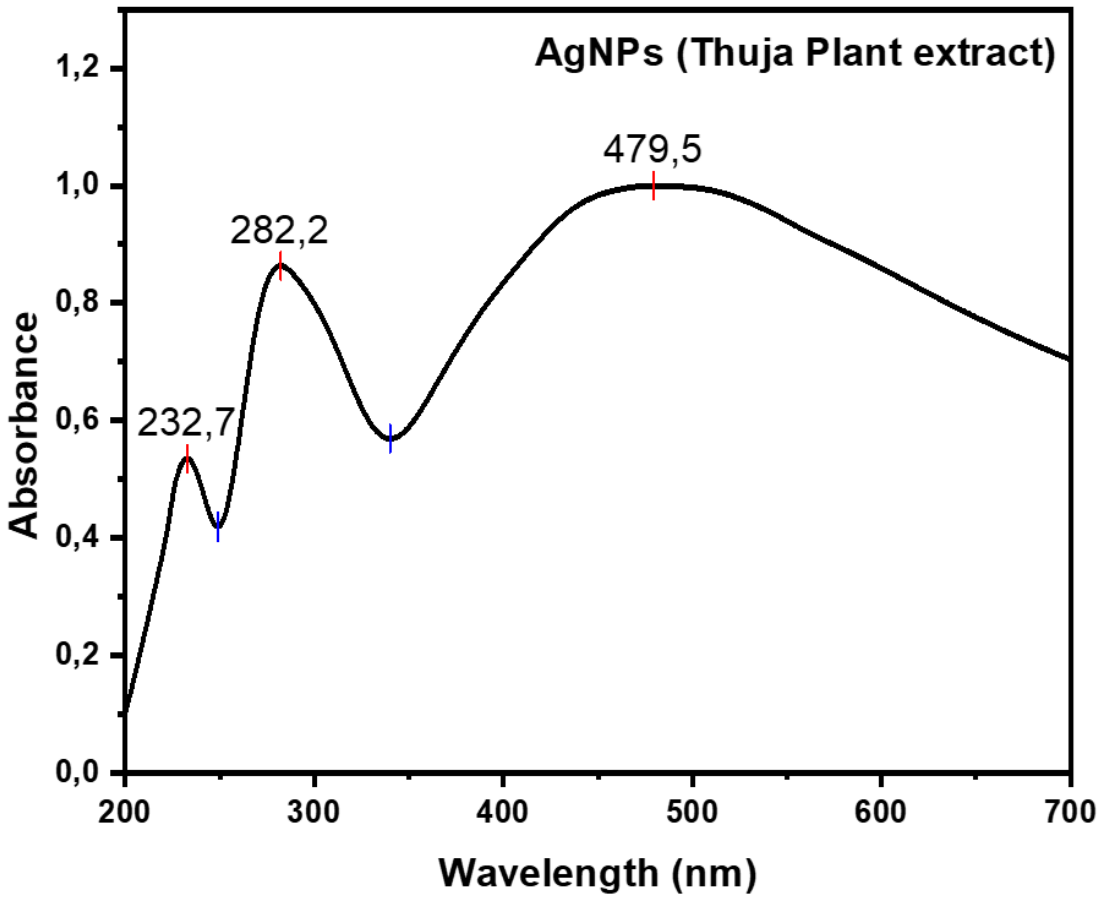

Figure 6.2. AgNP spectra graph of the thuja sample at 479.5 nm.

In this paper [19], the absorption spectra redshifts all the way toward the red region as the particles become more oblate, while [23][24] outlines possible LSPR ranges for different particle shapes.

6.3. Chemical method synthesis

Displayed is the peak at 320 nm belonging to very small, 20 nm nanoparticles, measured by my supervisor Prof. Erwan Yann Rauwel. However, looking at the spectra graphs in paper (3) in literature review 3.3., the 34 nm and 81 nm AgNPs both peaked at 410 nm with stronger absorption for the larger particles. The peak at 320 nm suggests that a size reduction of 14 nm yields a blueshift, if all other things such as interparticle spacing are accounted for. In this sample ethanol was used.

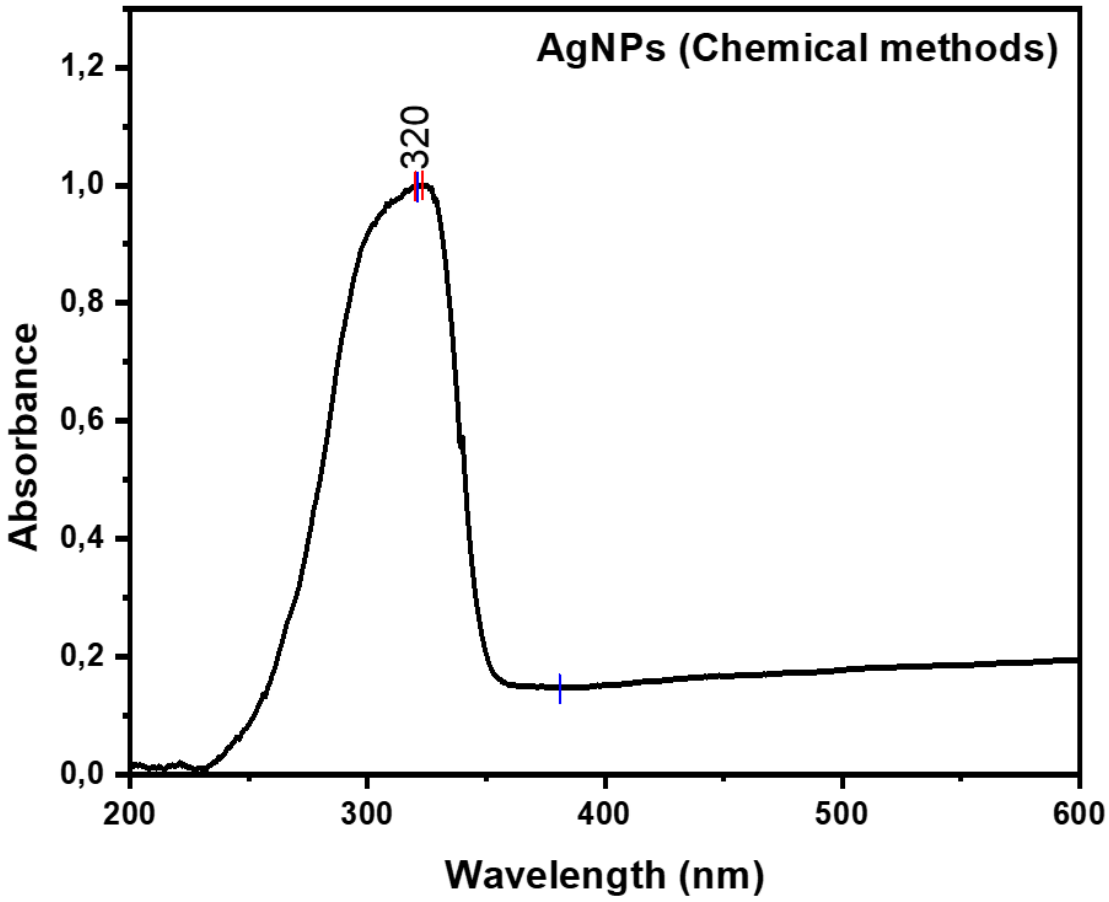

Figure 6.5. AgNP peak of 320 nm in the chemical method sample.

CONCLUSION

Nanoparticle morphology changes the LSPR peak. The synthesis method influences intrinsic properties. The dielectric environment affects the resonance wavelength. With interacting electric fields, we have absorption. Larger particles have higher absorption. The more e-fields interact with each other, the more there is a redshift.

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APPENDICES

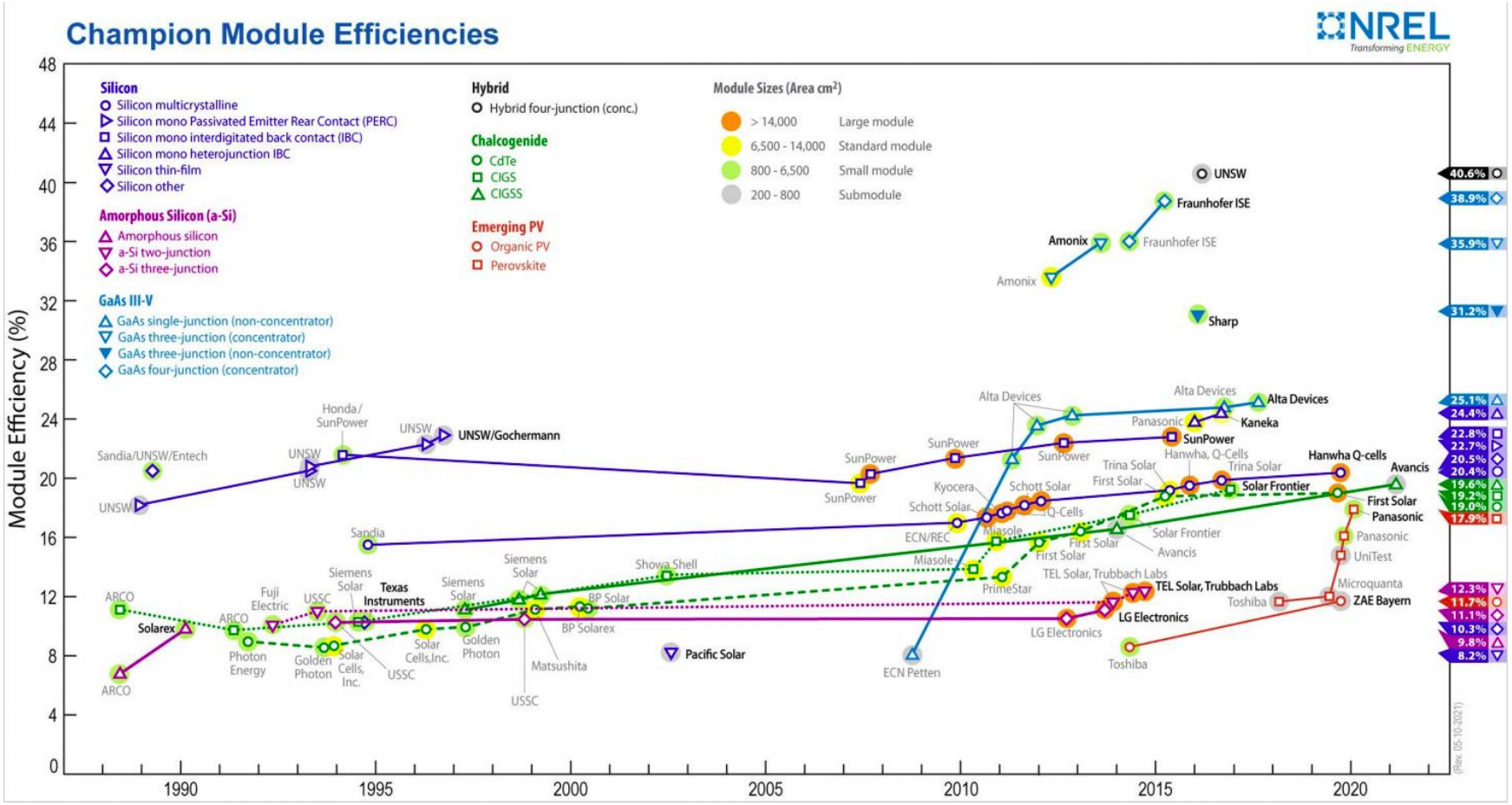

Figure A. Module efficiencies at NREL.gov**.** [A]

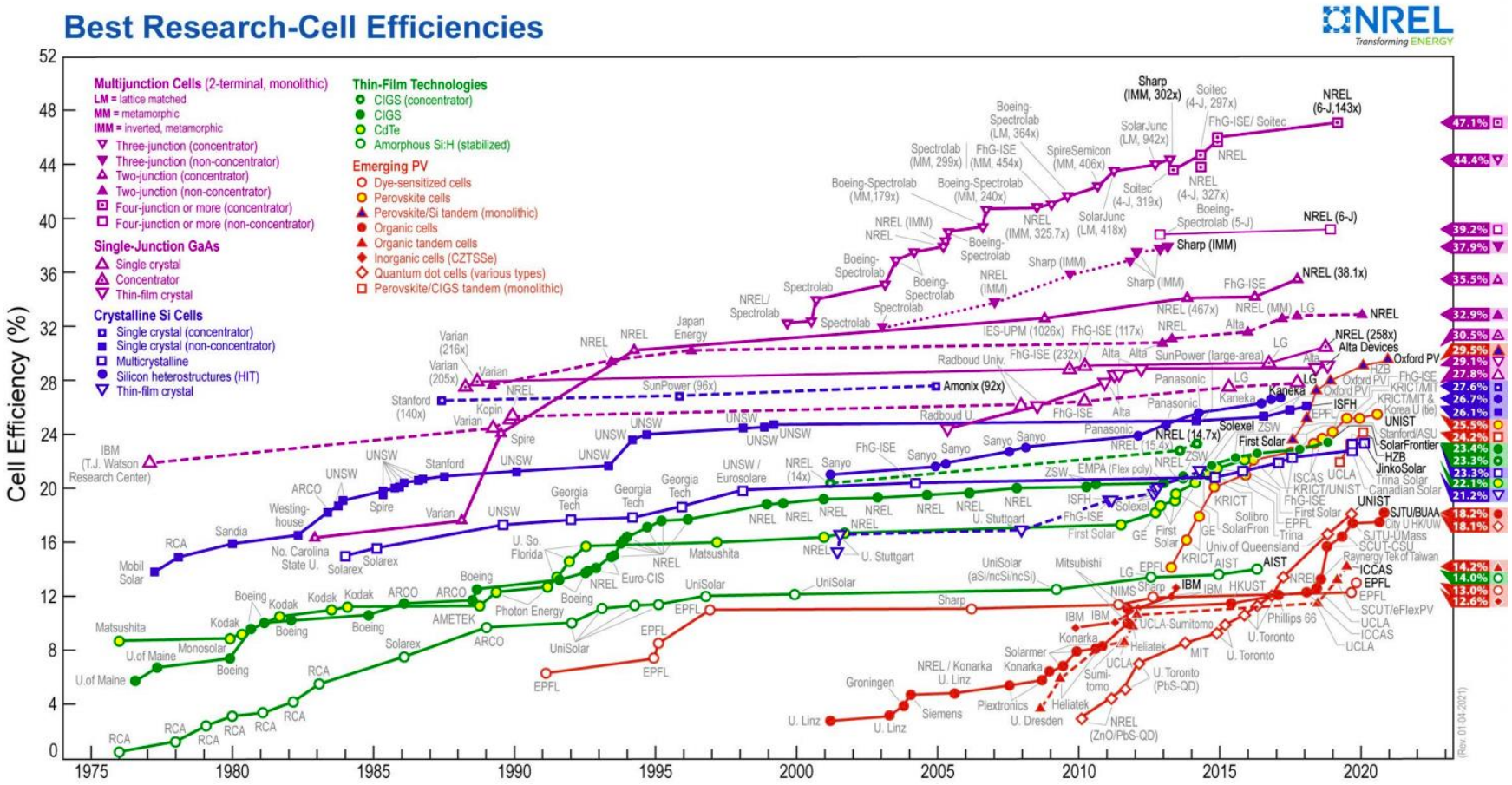

Figure B. Research-cell efficiencies at NREL.gov. [B]

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Mina, David Puusaag, sünnipäev 20/03/1991

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EXTRAS

Eestikeelne üldkokkuvõte

Päikesepaneelide osatähtsus maailma elektrienergia tootmisel hakkab suurenema. Loodetakse luua üha paremaid tehnoloogiad, milles sellise nimetusega ala nagu plasmoonika osatähtsus hakkab järk-järgult kindlamaks muutuma. Võti seisneb hõbemetallnanoosakeste kasutamises. Plasmoonika seisneb nanoosakeste kasutamises. See on valguse ärakasutamine päikeseenergia ning ühtlasi ka paneeli tõhusamaks muutmiseks. Laialdasi parendamisi on raporteeritud päikesepaneelide tehnoloogiates, kus nende võimsuse kasutegurit on suurendatud. Nanoosakeste kasutamine vähendaks ka tootmiskulusid võib-olla materjalide ning paneeli paksuse arvelt.

Selles töös uurin kolme AgNP (ingl *silver nanoparticle*, hõbemetallnanoosake) proovi, mis mulle anti, millest kaks on taimsetest ekstraktidest (vastavate nimetustega Artemisia ning Thuja) valmistatud, ning kolmas on keemiliselt sünteesitud puhas hõbemetallnanoosake. Uurin töö käigus neid osakesi sooritades UV-Vis Spectroscopy mõõtmiseid, kus mõõdan osakeste nähtava valguse ja ultraviolettkiirguse neeldumistugevust. Seda nimetatakse inglise keeles *absorption spectra*-ks. Uurin seonduvaid aspekte ning nähtusi nagu *plasmon resonants*, valgusresonants, valguse hajumine (ingl *scattering*) ning samuti ka hõbemetallosakesi ennast, nende tähtsust, omadusi ja rakendumisvõimalusi. Üldisemas mõttes uurin hõbemetallnanoosakeste kasutamist päikesepaneelide tehnoloogiates, tuues välja mõningaid näiteid, fakte ja teaduspõhiseid töid. Lõpetan töö proovide tulemuste analüüsimise ning mõningase aruteluga.

Nanotehnoloogia on oluline olnud viimastel aastakümnetel, on täheldatud uusi avastusi ning kasutuselevõtmisi: C_{60} kasutamine päikesepaneelide tehnoloogias, süsinik või grafiini (*graphene*) nanotorud ja viimaks plasmoonika, mis on kaasa aidanud teaduse ning tehnoloogiate rakendamisele ja uuendamisele. Plasmoonikat on palju uuritud, sest selles on palju potentsiaali, võimaldades head muutust ka päikesetehnoloogias. Plasmoonika võti seisneb valguse

ärakasutamises, selle õiges kasutamises. See tähendab valguse ärakasutamist nii, et selle juhtimine ja kontroll oleks võimalikult suur. Kõik toimub nanomõõtmetes. Hõbe aga on võimeline plasmonresonantsi või valgusresonantsi sooritama igal võimalikul valguse lainepikkusel, muutes selle ihaldatavaks metalliks.

Rääkides päikesepaneelide tehnoloogiatest üldisemalt, on kahte tüüpi pooljuhte: otsese keelutsooniga *(*ingl *bandgap* st energia kogus elektroni tõukamiseks juhtivustsooni, mõõdetakse eV-des, elektronvoltides) ja mitteotsese keelutsooniga. Otsese keelutsooniga materjalidel on suur neeldusmisvõime, kuna ei vaja palju energiat tõukeks, mitteotsesed seevastu aga vajavad rohkem energiat, kuna tsoonide vahemik on paigast ära – vektoriaalselt puudub korrapärasus. Seega vajavad mitteotsesed materjalid rohkem energiat elektroni juhtivustsooni viimiseks. Üheks selliseks materjaliks on tänapäeval enim kasutatud räni (Si, *silicon*), mida kasutatakse tavalistes päikesepaneeli tehnoloogiates. Seetõttu on neil materjali paksus paksem (180-300 µm), kuna vajavad rohkem energiat. Otsesed pooljuhid ja nende materjalid nagu CdTe (*Cadmium Telluride*), CIGS (*Copper Indium Gallium Selenide*), või a-Si (*amorphous silicon* ehk amorfne, mittekristalliline räni) on kõik *thin-film* tehnoloogiad. Neid tehnoloogiaid saaks sõltumata tehnoloogia tüübist parendada hõbemetallnanoosake. Nimelt suur osa valgusest jääb punasevalguse vahemikus suuresti või nõrgalt kasutamata – seda saaks hõbeosakeste kasutamine parandada.

Võti seisneb plasmoonika ärakasutamises, kus mängib rolli osake, keskkond, milles see paikneb, ning muud vähem olulised faktorid. Plasmon tähendab elektronide võnkumist sõltuvalt valguse lainepikkusest ruumis. Elektriväli ning magnetväljad vahetuvad ja liiguvad teineteisele risti ning vastassuunas omavahel, indutseerides samas ka vastassuunalist või samasuunalist liikumist osakese elektronides endas. Nii tekib osakese elektronide ühtne võnkumine, mida iseloomustab valguse sagedus ise. Resonantsi jõutakse aga siis, kui elektronide strukturaalne konfiguratsioon ühes osakese tasakaalustava jõuga jõuab valgusega harmooniasse. Selles olekus on indutseerunud elektriväli ülimalt tugev ning mõjutab ka kõrvalolevaid osakesi ning keskkonda. Kuna elektrone suunatakse ühest otsast teise, tekib dipool. Suurematel osakestel on suuremad ja eripärasemad poolimomendid. Elektrivälja võimendamist kasutabki plasmoonika ära, samuti valguse hajumist ruumi, mida täheldatakse suuremate osakeste puhul (kuna poolide momendid muutuvad). Kõike seda tehakse valgusetehnoloogia parendamiseks, et valguse energia neelduks

võimalikult hästi. Hea päikesetehnoloogia võtmeks on tõhus elektron-aukude tootmine, mis võiks soovituslikult juhtuda või toimuda alas, kus toimub laengute lahknemine ja sorteerimine (ingl *pn junction*) elektri tootmiseks. Seda saaksidki hõbeosakesed võimendada, võimendades selle ala elektrivälja, suurendades materjalide osakeste poolt saadavat energiat, tõugates elektrone välja, samuti mõjutades, võimendades ja pikendades sellega valguse kiiratavat energiat. Suuremad osakesed aga hajutavad valgust paremini (laiemalt), seega nende paigutamine oleks parim võib-olla materjali pinnale, kus korrigeeritud paikne suunamine neeldumisaladesse (alla) oleks optimaalne, või siis ka taha n-ö peegeldajatena, mida tehtigi ühes töös, millele olen ka käesoleva töö ingliskeelses osas viidanud (7).

Hõbe suudab erinevate kujude, suuruste ning dielektrise läbitavusega keskkondadega eri vahemikes plasmonresonantsi sooritada, kus on täheldatud neeldumiskiirguse sini- või punamuutust (ingl *blue-, redshift*). See tähendab resonantsi jõutakse pikemates või lühemates lainepikkustes. Resonants toimub pikematel lainepikkustel, mida suurema, erinevama ja keerukama kujuga on osake ja mida väiksema läbitavusega on keskkond. Kõik sõltub elektriväljade omavahelistest interaktsioonidest, kus toimub kas võimendamine või nõrgestamine (konstruktsioon, destruktsioon). Mõjutavad osakese enda elektronide liikumine, mass, laengute väljakujunenud momendid jne. Samuti on hõbe üks tõhusamaid resonantsi sooritajaid kõikide metallide seas.

Plasmon resonantsi sõltuvust keskkonnast kasutatakse ära, kasutades seda tuvastavates rakendustes, mis annab aimu analüüsitavast ainest, kus hõbeosake reageerib erinevalt erinevatele keskkondadele.

Liikudes edasi proovide analüüside juurde, siis on täheldusrikkamad proovid 455, 479.5 ja 320 nm valguse lainepikkusega tulemused. Suuremate lainepikkuste omad kuulusid rohelisel teel sünteesitud ainetele ning viimane keemilisel teel saadud ainele. Suurematel lainepikkustel olid ka lahuses orgaanilisele ainele kuuluvad resonantsitipud. Resonantsid lainepikkustel 455 ja 479.5 nm võivad olla tingitud suurematest, keerukama kujuga osakestest, samuti elektriväljade interaktsioonist orgaanilise materjaliga lahuses (dielektrilise keskkonna muutus). See võis olla ka tingitud osakeste ebaühtlasest suurusjaotusest. Näitena on välja toodud alapeatükis 3.3. mainitud töös nr 3. erinevate osakeste *UV-Vis Spectra* tulemused, näidates nende 34 nm ja 81 nm suurusjärgus diagramme, milles resonantsid paiknesid lainepikkuse 410 nm juures. 500 nm

suurused osakesed aga näitasid väga laia vahemikuga neeldusjaotust, tähistades nende suurust ja keerukat lilleõit meenutavat kuju. Resonantsi tulemuseks 320 nm lainepikkusel olid väga väikesed 20 nm osakesed. Tulemus oli tingitud arvatavasti osakeste vaheliste väljade interaktsioonist.

Proovide ettevalmistus seisnes nende hoolikas kaalumises, nende segamises lahustiga, ning seejärel segu peenestamises sonikaatoriga.